PRECOOLING PALLET LOADS OF SWEET CORN PACKED IN WIREBOUND CRATES

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PRECOOLING PALLET LOADS OF SWEET CORN PACKED IN WIREBOUND CRATES

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ABSTRACT

Four potentially practical techniques for cooling unit loads of sweet corn packed in wirebound crates were tested in series at three locations from November 1969 through January 1972: (1) Immersing the load in an agitated water bath, (2) simulating the conventional flood pan, (3) spraying with water only, and (4) circulating air through a water spray to provide an air-water mixture. The best cooling was obtained when the bottom three layers of a four-layer stack were immersed in an agitated water bath and water was showered onto the top layer from overhead spray nozzles. This technique, being ideal but impractical, was used to establish a standard cooling coefficient to which other techniques were compared. The technique of circulating air through a water spray, termed "hydraircooling" to denote the air-water mixture, proved to be comparable to the flood pan at a substantially reduced waterflow and superior to coarse spray nozzles at equal waterflow. Hydraircooling, with water discharging from medium nozzles at 120 gal/min/lb product, produced cooling nearly equal to that obtained by immersion cooling. Hydraircooling, developed during this research, is potentially practical as a method for precooling unit loads of sweet corn packed in wirebound crates, and it requires substantially less water than other methods.

INTRODUCTION

The annual farm value of fresh sweet corn sold in the United States increased from $20 million in 1945 to more than $68 million in 1970.[5] Precooling at the shipping point coupled with refrigerated transportation make it possible to deliver this highly perishable food to distant markets without costly deterioration in quality. However, methods of handling sweet corn through commercial marketing channels all too often result in serious quality losses before it reaches the consumer. Adequate refrigeration as soon as possible after harvest and throughout the marketing period is essential. It often takes several days to transport sweet corn from production areas to distant retail outlets. Without immediate temperature reduction and constant temperature management during this time, sweet corn deteriorates beyond consumer acceptability.

Sweet corn with consumer appeal is fresh looking, sweet, tender, and succulent. These attributes are measured in terms of the amount of sugar and moisture retained. According to Showalter,[6] un-

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[5]U.S. Department of Agriculture. Agricultural Statistics, 1945 and 1970.

[6]Showalter, R. K. 1960. Factors affecting quality maintenance of fresh sweet corn. Food Technology and Nutrition Mimeo Rep. 60–1, 13 pp.

cooled Florida sweet corn, stored at 75° F, loses 51% of its sugar in 18 hours as compared to 12% loss in 1 day and 20% in 5 days for sweet corn hydrocooled to 40° F and stored at 32° F. Moisture retention by fresh sweet corn depends in large measure on the temperature at which the corn is held. Winter[7] found that corn not precooled lost 8% moisture after 20 hours compared to no appreciable loss in precooled corn. These findings clearly show that sweet corn with maximum consumer appeal at the retail outlet must be thoroughly precooled at the shipping point and kept cool throughout the marketing period.

In Florida, sweet corn is customarily graded, packed in wirebound crates, and hauled on flat-bed trucks to a central plant for precooling and distribution. After it arrives at the plant, it is hydrocooled and loaded directly onto the appropriate transport vehicle.

In former practice, crates were individually unloaded by hand and loaded on a chain conveyor (fig. 1) to be carried through a hydrocooler. In the cooler, crates were partially submerged while water sprayed down on them from overhead. Cooling by this method was fast and efficient.

Present practice, however, is to handle the crated corn by forklift in palletized unit loads. The crop arrives at the distribution center already stacked on pallets, where it is precooled as a unit load (fig. 2).

This method of handling has been almost universally adopted because it results in a labor saving of about 50% over manual handling. To accompany unit-load handling, two types of unit-load hydrocooler have been developed. One type is a batch cooler (fig. 3) in which chilled water is sprayed onto the loads in a refrigerated room. One nozzle over each stack delivers about 90 gal/min of cold water for the stack of 30–40 crates, which is sometimes two pallets high.

In pilot-plant studies on such a system, Grizzell and Bennett[8] reported a very low cooling rate on sweet corn. Measuring at the cob center, they found that more than 3 hours were required to reduce the temperature from 90° F to 45° F, using water at approximately 38° F. This result is attributed in part to an insufficient quantity of water and in part to poor circulation of the water.

FIGURE 1.—Worker moving crate from conveyor to chain, which pulls it through hydrocooling tunnel.

The second common type of unit-load hydrocooler is a flow-through system in which the product is conveyed through cooling tunnels, where it is sprayed with cold water either from nozzles or flood pans. Such systems generally cool the product faster than the batch type and require less space, but they are less flexible in that product cooling time cannot be easily adjusted. It also requires that other cold storage space be available. Two variations of the flow-through system are shown in figures 4 and 5.

Most plants that handle sweet corn are equipped to provide the necessary precooling. However, conventional hydrocoolers require a substantial amount of water, need constant attention to maintain sanitation, are limited in the type of containers they will accommodate, and are not readily adaptable to the changes that inevitably occur in packaging and handling methods. This research was undertaken to investigate methods of precooling and if possible develop a new method that would

[7]Winter, J. D., Nyland, R. E., and Cox, R. W. 1954. Fresh sweet corn in the Midwest. Minn. Agric. Exp. Stn. Bull. 427, 28 pp.

[8]Grizzell, W. G., and Bennett, A. H. 1966. Hydrocooling stacked crates of celery and sweet corn. U.S. Dep. Agric., Agric. Res. Serv. [Rep.] ARS–52–12, 40 pp.

FIGURE 2.—Unloading pallet loads of sweet corn by fork truck for transport to the temporary storage area where they will await precooling.

FIGURE 3.—Batch-cooling unit loads of sweet corn packed in wirebound crates.

FIGURE 4.—Flow-through unit-load hydrocooler using spray nozzles for water distribution.

FIGURE 5.—Flow-through unit-load hydrocooler using flood pans for water distribution.

overcome some of the weaknesses of conventional hydrocoolers, yet achieve efficient and rapid cooling commensurate with shipping-point facility needs. Emphasis was placed on reducing water requirements.

DEVELOPMENT OF IMPROVED PRECOOLING METHOD

Seven test series, labeled A through G, comprising 53 individual test runs, were carried out at 3 locations from November 1969 through January 1972. Test treatments included (1) spraying water at selected flow rates with coarse, medium, and fine spray nozzles in different nozzle arrangements and spray patterns, (2) immersing the stack in agitated water, (3) showering with a conventional overhead flood pan, and (4) forcing air circulation at selected flow rates in combination with a water spray. Following test series A, carried out in the pilot plant at the Richard B. Russell Agricultural Research Center, Athens, Ga., a special cooling chamber was built and installed at the precooling plant of Pioneer Growers Cooperative, Belle Glade, Fla., where test series B was carried out. The equipment was then moved to the University of Florida campus and installed at the Agricultural Engineering Department, where test series C through G were performed.

Sweet corn packed in wirebound crates was stacked four layers high (32 crates) for test series A and B and five layers high (40 crates) for test series C through G on 4- by 4-foot pallets for unit-load handling. Copper-constantan thermocouples were placed in each layer throughout the stack to measure temperature at the center of the ear. Temperature was recorded with a 16-point recorder. After test series B, thermocouples remained in one location per series; a unit load was stacked at the beginning of each series and was not broken down until the series was completed.

Results of each test were analyzed and the findings used as a guide in setting up the succeeding series, making possible progressive refinement of experimental technique and selection of improved treatments. Experimental procedure is described in more detail in the sections dealing with individual test series.

Analytical Procedure

Test results are expressed in terms of cooling coefficients, half-cooling times, final predicted temperature, and coefficients of variation in temperature response within the load. The cooling coefficients and the half-cooling times describe cooling rates in relation to coolant temperature. They were evaluated on the basis of the ratio of the product to coolant temperature, according to the procedure used by Henry and Bennett.[9] This is a normalizing process that makes possible valid comparisons between test runs on test series of differing temperature conditions. However, experience demonstrates that meaningful comparisons result when both initial product and coolant are maintained at a constant temperature.

Half-cooling times are often more useful than cooling coefficients because they express the time required to reduce the product to a given temperature. The half-cooling times listed for each series in tables 1 through 8 were derived from the average of individual cooling coefficients within each stack. Average cooling coefficients by layer are given in the appendix. The coefficient of variation is a measure of uniformity of cooling throughout the stack.

Product temperature for any specified cooling time may be predicted by using the appropriate experimentally derived cooling coefficient and intercept-temperature ratio or by using the appropriate half-cooling time, z. The procedure takes the functional temperature-time relationship

$$T=T_1 e^{-C\Theta} \tag{1}$$

and transforms it into an equation for predicting temperature at 1 hour:

$$t_f=(t_i-t_o)e^{-(C+\log T_1)}+t_o. \tag{2}$$

In these equations, T is the temperature ratio $(t_f-t_o)/(t_i-t_o)$; T_1 is the intercept temperature ratio; C is the cooling coefficient; Θ is cooling time in hours; t_i is initial product temperature; and t_o is water temperature. If these values are known, the final predicted temperature, t_f, can be readily calculated. Final predicted temperature values given in this report were thus calculated for sweet corn initially at 90° F after cooling for 1 hour in water at 34° F. They reflect the average stack temperature. Similarly, the approach of reducing product temperature in half-cooling time steps yields a final predicted temperature which depends upon the number of half-cooling times selected. If, for exam-

[9]Henry, F. E., and Bennett, A. H. 1973. "Hydraircooling" vegetable products in unit loads. Trans. ASAE 16(4): 731–733, 739.

ple, the above sweet corn was cooled for three half-cooling times, it would be 62° F at the end of the first, 48° F at the end of the second, and 41° F at the end of the third half-cooling time.

Test Series A

In November 1969, we performed six test runs in an improvised hydrocooler in the pilot plant of the Russell Research Center (fig. 6). These tests were designed to evaluate the effectiveness of coarse spray nozzles with varying patterns and flow rates and to compare spray with immersion cooling. The single unit load was stacked four layers high, eight crates per layer. The stack was not broken, and thermocouples remained in the same positions during the entire series. Immediately following each run, except for the last run of the day, the load was reheated to the desired temperature in readiness for the next run.

In these tests we were primarily interested in comparing cooling rates obtained by immersing the stack in agitated water with those obtained by showering with spray nozzles and to investigate nozzle arrangement and water flow rates. The nozzles referred to as coarse nozzles for identification were the full-jet wide-angle type with a square spray pattern and capacity to deliver 18 gal/min each at 10 lb/in^2 pressure.

FIGURE 6.—Improvised experimental hydrocooler. Water was pumped from bottom of ice bunker (lower left), through spray nozzles (arrow), and returned to ice bunker with pump in center foreground.

The arrangement and spray pattern of five nozzles—one overhead and two on each side—is shown in figure 7; three nozzles—one overhead and one each side—in figure 8; and five nozzles—all overhead spraying downward—in figure 9. Figure 10 shows how water was circulated around the bottom three layers and sprayed onto the top layer of the immersed stack. Because of the buoyancy of the packed corn, it was necessary to keep the top layer above water level to hold down the stack, which had a tendency to float and separate.

Treatment outline and corresponding results for test series A are listed in table 1. From this test immersion cooling was found to be substantially faster and more uniform than spraying, and spraying from overhead was found to be superior to spraying from the sides at corresponding flow rates.

Coefficients of variation show that cooling was most uniform where the bottom three layers were immersed in agitated water, with water sprayed from overhead onto the top layer. This contrasts with the high variation in cooling rate occurring throughout the load, where only the bottom layer was immersed. Although the final predicted temperature for this test run indicates that cooling rate was nearly comparable to the immersion test, the high coefficient of variation suggests that part of the stack cooled poorly. This contrast is noted by comparing the respective cooling coefficients at individual thermocouple points listed in table A–1.

The average cooling coefficients listed by layers in table A–1 show that the bottom layer cooled faster than the other three layers in the four runs that were not immersed. Although there is no precise explanation for this phenomenon, it could logically be attributed to cool air convection currents in and around the lower part of the stack. The effect of air convection would be expected to be more pronounced in this location. The top layer, directly under the spray, is expected to cool faster than lower layers.

Test Series B

Thinking that natural air convection might be contributing to the increased cooling rate around the bottom of the stack, we decided to test the effectiveness of a mixture of air and water spray distributed around and through the stack by forced circulation, hence the term "hydraircooling." Accordingly, we designed and built an experimental precooler which we called a hydraircooler.

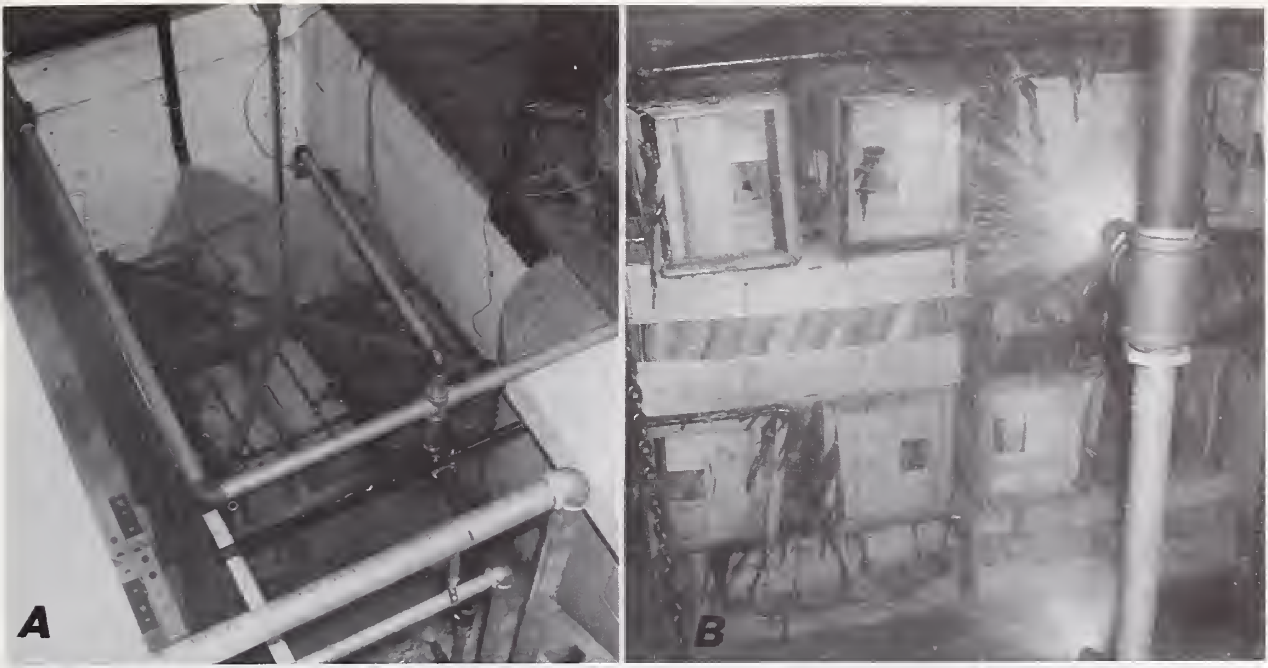

FIGURE 7.—Experimental hydrocooler having five coarse spray nozzles, one overhead and two on each end. *A*, overhead view; *B*, side view.

TABLE 1.—*Test series A: Hydrocooling of unit loads*

Run	Number of nozzles	Nozzle arrangement and description[1]	Waterflow rate (gal/min)	Variation coefficient (%)	Temperature ratio at intercept	Half-cooling time (hours)	Final predicted temperature (° F)
A–1	5	1 overhead, 2 each side	.65	32.6	1.00	0.60	51.50
A–2	5	1 overhead, 2 each side	.90	33.6	1.14	.63	51.39
A–3	3	1 overhead, 1 each side	.53	39.4	.94	.53	49.85
A–4	3	3 overhead, bottom layer immersed	.55	55.8	1.18	.39	41.47
A–5	3	3 overhead, 3 layers immersed	.55	19.1	1.02	.31	39.78
A–6	5	All overhead	.90	29.2	1.03	.45	45.54

[1]Coarse nozzles used in all tests of this series.

In February 1970, we installed the experimental hydraircooler (fig. 11) at the precooling and shipping plant of Pioneer Growers Cooperative, Belle Glade, Fla., and proceeded with test series B. In this series, we completed 6 test runs on unit loads of packed sweet corn containing 32 crates each, stacked 4 layers high.

In the first two runs, five coarse nozzles (from test series A) spaced equidistantly on a straight pipe and spraying downward from overhead were used. In the remaining runs with sweet corn (and two celery runs), nozzles designed to provide a very fine mist (a particle size of 150 μm or less when operating against a pressure of 20 lb/in^2 or more) were spaced on pipes radiating from a center overhead plenum to provide for uniform spray distribution. The spray pattern is shown in figure 12.

Air was circulated by a small centrifugal blower

discharging at the top edge of the cooler, so placed as to draw all of the air through the stack and into the pallet. The pallet was connected to the air plenum at the bottom edge of the cooler (fig. 12). Air circulation with this system was poor because water accumulated on the floor of the cooler and restricted airflow from the pallet into the plenum. Airflow was not measured; hence, the test description simply specifies "yes" or "no" to indicate whether there was air circulation or not.

Test treatments and results for the sweet corn tests are given in table 2. The data reveal two important facts: first, all other things being equal, circulation of air seems to increase the cooling rate; and second, using fine spray nozzles, waterflow can be reduced without jeopardizing cooling rate. Comparing runs B–1 and B–3 for the coarse and B–8 with B–9 for the fine nozzles, air appears to be a significant factor contributing to the increased cooling rates. Also, cooling at a waterflow rate of 65 gal/min with fine nozzles compared favorably with 100 gal/min where coarse nozzles were used. However, clogging of the fine nozzles presented a problem.

To determine whether it is better to draw all the air down through the stack from the top or to permit the air-water mixture to circulate around the stack

FIGURE 9.—Experimental hydrocooler having five coarse nozzles spraying downward.

FIGURE 8.—Experimental hydrocooler having three coarse spray nozzles in a downward overhead and side-angle pattern.

FIGURE 10.—Experimental hydrocooler in which three layers are immersed in an agitated bath and the top layer is sprayed by three nozzles in a downward side-angle pattern.

TABLE 2.—*Test series B: Hydro/hydraircooling of unit loads*

Run	Number of nozzles	Nozzle description	Waterflow rate (gal/min)	Air	Variation coefficient (%)	Temperature ratio at intercept	Half-cooling time (hours)	Final predicted temperature[1] (° F)
B–1	5	Coarse	100	No	40.0	1.16	0.64	51.35
B–3	5	..do	100	Yes	23.4	.87	.38	45.31
B–6	27	Fine	65	Yes	40.8	1.05	.68	53.77
B–8	27	..do	65	Yes	29.2	.91	.40	45.60
B–9	27	..do	65	No	31.4	1.09	.68	53.33
B–11	27	..do	62	Yes	36.0	1.01	.57	50.37

[1]After cooling for 1 hour with corn initially at 90° F and water at 34° F.

FIGURE 11.—Experimental hydraircooler as set up for testing at the precooling plant of Pioneer Growers Cooperative, Belle Glade, Fla.

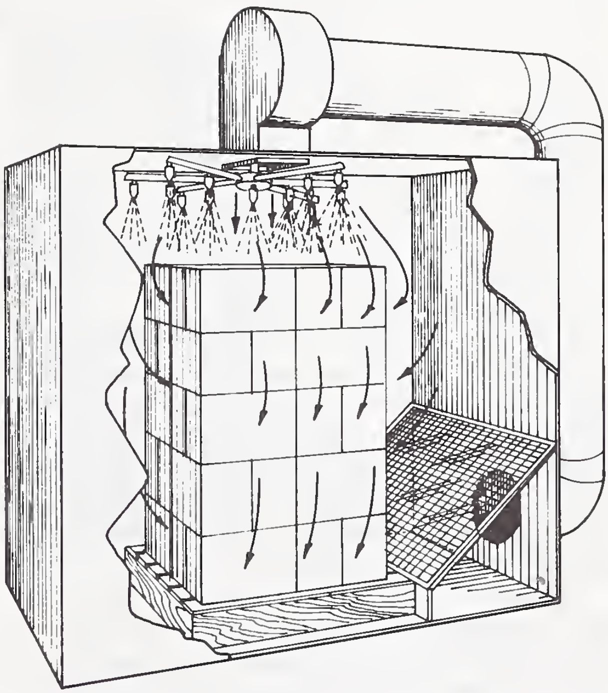

FIGURE 12.—View of air system showing pallet used as a duct for moving air into plenum.

and be drawn in from the sides as well as the top, test runs B–6 and B–8 were conducted identically except for a polyethylene sheet wrapped around the sides of the stack in run B–6, forcing all the air through the stack from the top. Results (table 2) indicate that allowing the air-water mixture to envelop the stack and enter from all sides is better than restricting it to top entry only. In addition to a substantially improved cooling rate, temperature variation throughout the stack was reduced. The cooling coefficients by layer for test runs B–6 and B–8, given in table A–2, provide added insight into the phenomenon of the faster cooling at the bottom of the stack. Slower cooling of the bottom layers during run B–6 is evidence that the cooling effect attributable to air convection at the bottom layers was prevented by the polyethylene film wrap. Two significant findings from this series are that forced circulation of air around and through the stacked load in a cooler improves cooling rate, and it is better to allow the air to enter the stack from all sides than to restrict it to top entry only. We also obtained information about the relationship of airflow to nozzle size, spray pattern, and waterflow rate.

This series did not provide enough data to support conclusions about the increased cooling effect at the bottom of the stack or to find the best relationship between airflow and waterflow rates, nozzle size, and the use of nozzles as compared to a flood pan. These questions were investigated in a following series.

One problem experienced in this series was lack of control of product and chill-water temperature. The temperature of incoming product was often less

than 20° higher than that of the water—a smaller margin than desirable for good estimation of cooling parameters. To provide better control, we moved the experimental cooler to the Agricultural Engineering Department at the University of Florida. All subsequent tests were performed at this location.

Test Series C

In June 1970, we made eight test runs to determine how the spray characteristics of coarse and medium nozzles related to airflow, waterflow, and cooling rate. The coarse nozzles were like those used in test series A. The medium nozzles delivered 5 gal/min each in a 360° conical pattern at 10 lb/in^2 operating pressure. The medium nozzles reduced the problem of clogging experienced with the fine nozzles, and fewer of them were required to get the necessary waterflow. They also produced a fog that enveloped the stack. All tests were run with the spray directed down from overhead. The air system was the same as in test series B.

Beginning with this series and continuing for the remainder of the program, each series was run on a single unit load of 40 crates stacked 5 layers high. Immediately before each test run, the load was heated to the desired initial temperature. Thermocouples were left in place throughout each series. This improved the consistency of temperature data within the series.

The medium nozzles did not deliver 100 gal/min and so could not be compared with the coarse nozzles at that flow rate. Nevertheless, as noted in table 3, the medium nozzles gave the faster cooling, even with the reduced waterflow.

Test Series D

The test runs of this series included four with medium nozzles spraying down, as previously described, and two with a specially devised flood pan (fig. 13) built to simulate the conventional commercial flood pan hydrocoolers. The objectives were (1) to compare waterflow rates, with and without air, for equal spray conditions and (2) to compare the flood pan with spray nozzles. Treatments and results are presented in table 4.

The results show that 100 gal/min through medium nozzles is substantially superior to 50 gal/min, with or without air, and the effect of air is less at the lower waterflow rate. Cooling is faster with the medium spray nozzles than with the flood

FIGURE 13.—Experimental flood pan for testing cooling rate of unit loads of packed sweet corn.

pan at 100 gal/min. Effect of waterflow rate is seen by comparing runs D–3 with D–4 and D–5 with D–6. The effect of air is evident in comparison of runs D–3 and D–5 but is less pronounced at the lower waterflow rate in D–4 and D–6. The variation coefficients indicate that cooling is more uniform at higher waterflow rates. The cooling coefficients given in table A–4 show a greater spread between layers at the lower rate of waterflow than at the higher rate. Cooling of the bottom layers is substantially reduced at 50 gal/min. The increased cooling effect at the bottom does not appear in this series.

Test Series E

Test series D showed that circulating air, combined with a medium water spray directed down onto the stack, improved the cooling rate. However, the capacity of the small fan was not adequate. We installed a larger fan with a variable-speed motor capable of circulating air through the system at rates of flow up to 2,760 ft^3/min, sealed the unit to prevent air from escaping, and rigged the pumping system to supply up to 100 gal/min of cold water to medium nozzles, spraying down onto the top of the stack. The airblast was also directed down on top of the stack, but was circulated to allow air to enter the stack from all sides as well as the top.

Six test runs were completed in November 1970. Our primary objective was to determine if cooling rate could be improved by increasing the air circulation with the medium spray, and if so, to find the minimum effective rate of waterflow. Accordingly, waterflow rates of 50 and 100 gal/min were tested in

TABLE 3.—*Test series C: Hydro/hydraircooling of unit loads*

Run	Number of nozzles	Nozzle description	Waterflow rate (gal/min)	Air	Variation coefficient (%)	Temperature ratio at intercept	Half-cooling time (hours)	Final predicted temperature (° F)
C-1	5	Coarse	100	Yes	35.79	0.96	0.74	56.29
C-2	5	..do	100	No	18.01	.94	.52	49.70
C-3	5	..do	100	Yes	31.24	1.00	.55	50.04
C-4	5	..do	65	Yes	32.31	.89	.48	48.86
C-5	19	Medium	80	Yes	37.28	.96	.51	48.95
C-6	19	..do	50	Yes	35.21	.96	.56	50.69
C-7	19	..do	80	No	32.16	1.00	.49	47.54
C-8	19	..do	80	Yes	33.31	.98	.46	46.75

TABLE 4.—*Test series D: Hydro/hydraircooling of unit loads*

Run	Number of nozzles	Treatment description	Waterflow rate (gal/min)	Air	Variation coefficient (%)	Temperature ratio intercept	Half-cooling time (hours)	Final predicted temperature (° F)
D-1	—	Flood pan	100	—	26.09	0.90	0.36	43.97
D-2	—	..do	100	—	32.48	1.00	.44	45.65
D-3	19	Medium nozzles	100	No	20.59	.97	.37	43.25
D-4	19	..do	50	No	27.39	.95	.44	46.35
D-5	19	..do	100	Yes	23.44	1.06	.39	42.45
D-6	19	..do	50	Yes	33.91	.95	.43	45.99

conjunction with airflow ranging from 500 to 1,000 ft³/min. Airflow was measured by traversing the horizontal cross-sectional area with a van anemometer, and the fan was calibrated to allow control of air delivery in increments of 1,000 ft³/min. A malfunction caused a temporary fan shutdown during test run E-2; this run was duplicated as run E-4 to complete the data in the sequence of airflow-rate tests. Table 5 gives airflow data versus fan speed.

TABLE 5.—*Static-pressure drop across the fan for various airflows and fan speeds for circulating air through hydraircooler*

Measured airflow (ft³/min)	Fan speed (r/min)	Static pressure (in H_2O)
1,000	400	0.18
1,600	700	.55
2,600	1,150	1.42
2,750	1,350	1.98

The results of test series E, given in table 6, show that cooling rate is correlated with volume of air circulated for both the waterflow rates. Waterflow of 100 gal/min is clearly superior to 50 gal/min. Even this limited number of test runs, when subjected to statistical analysis using each of the 14 data points within each run, shows a significant effect of air and waterflow on cooling rate.

TABLE 6.—*Test series E: Hydraircooling of unit loads*

Run	Number of nozzles	Waterflow rate (gal/min)	Airflow rate (ft³/min)	Variation coefficient (%)	Temperature ratio at intercept	Half-cooling time (hours)	Final predicted temperature (° F)
E-1	19	100	500	51.4	0.996	0.40	44.02
E-2	19	100	600	36.0	1.001	.39	43.38
E-3	19	100	750	40.5	1.011	.37	42.49
E-4	19	100	600	37.0	.990	.37	42.94
E-5	11	50	750	36.8	.963	.45	46.55
E-6	11	50	1,000	37.0	.995	.46	46.33

[1]Medium nozzles were used in this test series.

Test Series F

In June and July of 1971, we completed 12 test runs in 2 sets, runs F–1A through F–5A and F–1B through F–7B (table 7). Our objective in the first set was to compare cooling rates with the flood-pan system and waterflow rates used commercially with hydraircooling, using medium spray nozzles. Commercial hydrocoolers employing the conventional flood pan circulate from 250 to 300 gal/min/unit load. The second set was run to confirm the previously noted correlation between cooling rate and volume of air circulated and to verify airflow calibrations.

From table 7, cooling response is seen to be less predictable with the flood pan than with the air and water spray system. The flood pan's cooling the load faster at 250 gal/min than at 400 gal/min defies explanation. Consistent results do tend to bear out that 100 gal/min in the flood pan is not adequate. Indications point toward the need for at least 250 gal/min, and possibly more, to achieve cooling comparable to that obtained with the optimum air-water mixture using medium nozzles. In contrast, 100 gal/min through medium nozzles at high airflow produced cooling rates comparable to those obtained by immersion.

Test Series G

In January 1972, we completed eight test runs as the final series in this phase of the program. The tests, as outlined in table 8, were designed primarily to clear up the illogical results of the flood-pan tests in the previous series. Accordingly, the three immediately preceding flood-pan tests were duplicated, except for a small change in waterflow for one test. The order of tests was reversed from the previous series in an effort to observe any possible effects on cooling rate from repeated heating and cooling of the unit load.

Again, the unpredictable response in the flood-pan tests defied rational interpretation. There appears to be more variation in temperature throughout the stack with flood-pan cooling at the low flow rates than with hydraircooling at equal flow or with flood-pan cooling at higher rates of flow. No effect on cooling rate from repeated heating and cooling was observed.

CONCLUSIONS

Of the seven test series successfully completed, the first one and the last two were the most productive. The first established the cooling rate to be used as the goal in further tests. It was obtained by immersing the load in an agitated water bath. However, because immersion cooling, while ideal for cooling unit loads, is not practical, tests were directed toward achieving the goal by more practical means. Progressive refinement of experimental technique and selection of improved treatments resulted in the nearest achievement of the goal during the final two test series.

A combination of forced-air circulation and water spray to produce a dense air-water mixture that completely envelops and penetrates the stack was found to be an effective, practical method for precooling unit loads of sweet corn. The coarse nozzles tested did not produce a sufficiently small particle size, whereas the fine nozzles gave trouble with clogging. Medium nozzles, however, produced a

TABLE 7.—*Test series F: Hydro/hydraircooling of unit loads*

Run	Number of nozzles	Treatment description	Waterflow rate (gal/min)	Airflow rate (ft³/min)	Variation coefficient (%)	Temperature ratio at intercept	Half-cooling time (hours)	Final predicted temperature (° F)
F–1A	—	Flood pan	400	(1)	29.09	1.03	0.48	46.62
F–2A	—	..do	250	(1)	34.39	1.03	.37	42.04
F–3A	—	..do	100	(1)	38.20	1.04	.48	46.49
F–4A	19	Medium nozzles	100	750	39.42	1.05	.45	45.41
F–5A	19	..do	100	1,000	39.01	1.02	.44	43.83
F–1B	19	..do	100	1,000	38.95	.98	.42	44.97
F–2B	19	..do	100	1,600	35.61	.99	.39	43.63
F–3B	19	..do	100	2,600	37.45	1.02	.37	42.21
F–4B	19	..do	100	2,760	35.73	1.01	.35	41.43
F–5B	19	..do	120	2,760	37.35	1.01	.34	41.35
F–6B	19	..do	120	1,600	34.11	1.02	.33	40.72
F–7B	19	..do	120	1,000	30.82	1.01	.33	40.86

[1] Air was not circulated during runs with flood pan.

TABLE 8.—*Test series G: Hydro/hydraircooling of unit loads*

Run	Number of nozzles	Treatment description	Waterflow rate (gal/min)	Airflow rate (ft³/min)	Variation coefficient (%)	Temperature ratio at intercept	Half-cooling time (hours)	Final predicted temperature (° F)
G–1	—	Flood pan	400	(1)	27.28	1.099	0.39	42.32
G–2	—	..do.............	250	(1)	26.51	1.072	.46	45.61
G–3	—	..do.............	125	(1)	32.92	1.011	.40	43.63
G–4	19	Medium nozzles ..	120	2,760	30.73	1.102	.42	43.55
G–5	19	..do.............	120	2,500	26.75	1.159	.48	45.30
G–6	19	..do.............	120	1,600	30.56	1.114	.40	42.38
G–7	19	..do.............	100	2,760	25.91	1.061	.41	43.48
G–8	19	..do.............	100	1,600	25.89	1.070	.42	43.78

[1]Air was not circulated during runs with flood pan.

suitable particle size for effective cooling and did not give any trouble with clogging. Thus, water, flowing through medium nozzles at 120 gal/min/unit load, mixed with air circulated at 1 ft³/min/lb product, effectively precooled unit loads of sweet corn packed in wirebound crates.

Because of the erratic results in the flood-pan tests, logical conclusions with respect to relative effect of waterflow rates are impossible. Evidence does tend to suggest, however, that at least 250 gal/min/unit load are required to produce cooling equal to immersion or optimum hydraircooling.

Because of inherent variation, comparisons among series are less reliable than comparisons within series. Data from similar test runs in different series sometimes showed greater variation than dissimilar runs within a series.

The fastest and most effective way of uniformly cooling unit loads of sweet corn packed in wirebound crates is by immersing the load in thoroughly agitated chilled water.

When used in the proper mass-flow rate relationship, a mixture of air and water produced by circulating air through a spray of medium particle size, will cool almost as rapidly and uniformly as immersion. Maximum cooling is achieved with the air-water mixture enveloping the stack, entering from all sides.

Hydrocooling by means of conventional overhead flood pans will rapidly and effectively cool unit loads of packed sweet corn, but approximately three times as much water is required to achieve results comparable with the air-water (hydraircooling) system.

APPENDIX.—COOLING COEFFICIENTS FOR TEST SERIES

Average cooling coefficients are reported for each layer and for each run of test series A–G.

TABLE A–1.—*Test series A*

Layer[1]	Run					
	A–1	A–2	A–3	A–4	A–5	A–6
1	1.17	1.27	1.55	2.27	1.83	1.80
2	.86	.78	.80	1.36	2.38	1.20
3	1.31	1.50	1.05	1.89	2.44	1.51
4	1.35	1.52	1.57	3.52	2.51	2.08
Average	1.16	1.30	1.20	2.18	2.29	1.61

[1]Layers are numbered from top to bottom.

TABLE A–2.—*Test series B*

Layer	Run					
	B–1	B–3	B–6	B–8	B–9	B–11
1	1.86	1.91	1.36	1.67	1.52	1.65
2	1.29	1.31	1.24	1.24	.94	1.17
3	1.20	1.46	.99	1.76	1.00	.73
4	.77	1.26	.83	1.36	1.20	1.40
Average	1.32	1.46	1.09	1.48	1.15	1.24

[1]Layers are numbered from top to bottom.

TABLE A-3.—*Test series C*

Layer[1]	Run							
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8
1	1.14	1.25	1.30	1.37	1.28	1.39	1.56	1.65
2	1.11	1.46	1.63	1.57	1.86	1.47	1.91	1.85
3	.59	1.01	1.09	.90	.94	.86	.99	.98
4	.74	1.08	.90	1.00	.98	1.03	1.15	1.23
5	.79	1.23	1.22	1.16	1.18	1.02	1.43	1.51
Average	.88	1.21	1.25	1.21	1.28	1.17	1.42	1.46

[1]Layers are numbered from top to bottom.

TABLE A-4.—*Test series D*

Layer[1]	Run					
	D-1	D-2	D-3	D-4	D-5	D-6
1	1.89	1.92	2.19	1.94	2.44	2.02
2	1.62	1.74	1.68	1.46	1.88	1.35
3	1.69	1.73	1.91	1.59	2.13	1.71
4	1.78	1.37	1.72	1.42	2.00	1.44
5	1.14	1.09	1.36	.89	1.32	1.49
Average	1.62	1.57	1.77	1.46	1.95	1.49

[1]Layers are numbered from top to bottom.

TABLE A-5.—*Test series E*

Layer[1]	Run					
	E-1	E-2	E-3	E-4	E-5	E-6
1	1.64	1.84	2.07	1.91	1.63	1.71
2	1.67	1.79	1.97	1.93	1.45	1.58
3	2.04	2.11	2.29	2.19	1.70	1.75
4	2.07	1.77	1.87	1.77	1.35	1.36
5	1.15	1.43	1.34	1.36	1.15	1.17
Average	1.72	1.79	1.91	1.83	1.46	1.51

[1]Layers are numbered from top to bottom.

TABLE A-6.—*Test series F-A*

Layer[1]	Run				
	F-1A	F-2A	F-3A	F-4A	F-5A
1	1.67	2.15	1.68	1.91	2.05
2	1.67	2.10	1.73	1.69	1.93
3	1.35	2.15	1.76	1.82	1.98
4	1.21	1.37	1.21	1.21	1.31
5	1.70	2.12	1.38	1.64	1.59
Average	1.52	1.97	1.54	1.64	1.76

[1]Layers are numbered from top to bottom.

TABLE A-7.—*Test series F-B*

Layer[1]	Run						
	F-1B	F-2B	F-3B	F-4B	F-5B	F-6B	F-7B
1	1.68	1.93	2.17	2.45	2.48	2.53	2.45
2	1.70	1.77	2.01	2.06	2.15	1.74	2.21
3	1.42	1.49	1.64	1.67	1.63	1.80	1.94
4	1.83	2.00	2.19	2.16	2.13	2.23	2.18
5	1.31	1.46	1.58	1.69	1.68	1.66	1.56
Average	1.61	1.75	1.94	2.03	2.04	2.14	2.11

[1]Layers are numbered from top to bottom.

TABLE A-8.—*Test series G*

Layer[1]	Run							
	G-1	G-2	G-3	G-4	G-5	G-6	G-7	G-8
1	2.74	2.26	2.57	2.63	2.42	2.79	2.52	2.47
2	1.97	1.62	1.66	2.01	1.97	2.28	2.05	2.00
3	2.12	1.71	1.88	1.81	1.66	1.94	1.68	1.72
4	1.54	1.30	1.20	1.27	1.24	1.27	1.28	1.29
5	1.65	1.33	1.39	1.61	1.46	1.75	1.64	1.58
Average	2.04	1.67	1.77	1.92	1.80	2.07	1.89	1.86

[1]Layers are numbered from top to bottom.

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